Compositional Mapping of Jupiter's Satellite Io Utilizing High Speed Multifilter Photometry during Mutual Satellite Occultations, 1990-1991

Robert M. Nelson (1)

Brad D. Wallis (1)

Edwin S. Barker*(2)

Linda J. Horn (1)

William D. Smythe (1)

Arthur L. Lane (1)

Bruce W. Hapke (3)

1 Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena CA 91109

2 McDonald Observatory
University of Texas at Austin
Austin TX, 78712

3 Department of Geology and Planetary Science
University of Pittsburgh
Pittsburgh PA 15260

* Present address Code SL, NASA Headquarters, Washington DC 20546

Number of Pages: 17

Number of Figures: 10

Number of Tables: 1

Submitted to Icarus, 29 Oct. 1993

Corresponding Address:

Robert M. Nelson
183-501 Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA, 91109
818-354-1797

Proposed Running Head: Io, Surface Compositional Mapping

Abstract

We observed selected mutual occultations of Jupiter's satellites in 1990-1991 and we used the occultation profiles to constrain the areal distribution of selected spectrally active compounds on Io's surface. We performed high speed photometry of Io at four wavelengths while it was being occulted by another Galilean satellite. The wavelengths of the filters that we used for this work were 0.305 μm, 0.345 μm, 0.45 μm, and 0.56 μm. These wavelengths were selected so as to constrain the areal distribution on Io of what are believed to be its two major surface constituents. These are sulfur and/or sulfur bearing compounds and sulfur dioxide (SO_2) frost. During a typical occultation, a Galilean satellite whose spectral properties are well defined, passed in front of Io, gradually blocking the sunlight reflected by Io from reaching an earth-based observer. The photometric contribution of the occulting object was" removed from the combined signal. The observed occultation brightness variations were compared to curves produced by synthesized occultations that would be expected assuming a two component surface, where one component is an unknown mixture of sulfur bearing materials and the other is SO_2 frost. By employing a trial and error curve fitting process a compositional distribution map was produced which modeled the variation of SO_2 frost relative to the sulfurous materials. This was done by simulating different distributions of sulfur bearing materials and SO_2 frost on Io's surface and calculating the change in relative intensity in the light reflected from Io and the occulting object during each eclipse. On Io's trailing hemisphere, we find that the region north of the equator between latitudes O and 60 degrees and between 180 and 270 degrees longitude to be highest in concentration of SO_2 frost. This distribution is consistent with longitudinal constraints on SO_2 frost abundance determined by observations with the International Ultraviolet Explorer spacecraft. It also coincides with the highly reflective "white areas" seen in the Voyager spacecraft television images. Due to the circumstances of the occultation geometry we were unable to observe Io's leading hemisphere (longitudes 0-180 degrees while it was being occulted. Therefore, this work is only relevant to Io's trailing hemisphere.

INTRODUCTION

Reflectance spectroscopy has contributed significantly to the identification and areal localization of species which comprise the surfaces of the outer satellites of the solar system. In the case of Jupiter's satellite Io, its spectral geometric albedo has been well determined by observations from groundbased telescopes, from earth orbit, and by the Voyager spacecraft. Spectrophotomet ri c observations from groundbased telescopes are consistent with the hypothesis that the surface of Io is composed of elemental sulfur (Wamsteker *et al.*, 1974) in one or more of its many allotropic forms (Nelson and Hapke, 1978) and sulfur dioxide frost (Fanale *et* al. 1979, Smythe *et* al., 1979, Hapke, 1979). Other materials that may be present include lower oxides of sulfur (Hapke, 1989) and a minor contribution of sodium and potassium bearing sulfur compounds. Io is surrounded by a torus of material which contains all of these species in ionized form. This lends further support to the hypothesis that these compounds are found in abundance on Io's surface because material is most probably being supplied to the torus from Io due to interaction between the Jovian magnetosphere and Io's surface (Matson *et* al. 1974).

While the Pioneer and Voyager missions to the outer solar system produced high spatial resolution images of Io at a few broadband filter wavelengths, groundbased spectrophotometry still provides the highest spectral resolution information at many wavelengths of great importance. Furthermore, groundbased observations are the only way in which temporal changes on Io can be adequately studied until the arrival of the Galileo spacecraft to the Jupiter environs in 1996-an event which will permit comparison between the Galileo data and the Voyager data from nearly two decades earlier.

Spectrophotometric observations from earth or near-earth orbit have been used to identify the principal absorption species which cover Io's surface. The spectral geometric albedo of Io from groundbased and earth orbiting instruments are shown in Fig 1a,b. Figure la is a relative reflection spectrum from 0.26 to 0.34 μm of Io from the IUE spacecraft ratioed to a solar spectrum (Nelson *et* al., 1987). Figure 1b is a groundbased spectrum of Io's leading hemisphere ratioed to a solar spectrum (Nelson and Hapke, 1978). The resulting spectral geometric albedo shows the wavelength of the reflection spectrum of the materials on Io's surface. Sulfur and SO_2 frost, the principal candidate mineral species for Io's surface, have absorption features that are in the 0.3 μm- 0.7 μm spectral range (See Fig 2). One of these materials, SO_2 frost, has a strong absorption shortward of 0.33 μm. In this paper the non SO_2 material will be referred to as 'sulfur' even though it may contain other compounds which have similar spectral properties. This sulfur-bearing material has an absorption feature in the 0.4 μm- 0.7 μm range. The allotropic form of the sulfur may be S_3, S_4, S_5, S_6, or S_8 of which each allotrope has a distinct absorption band in the region between 0.4 and 0.5 μm (e.g. Meyer 1972; Nelson *et* al., 1990).

The spatial resolution obtainable from earthbased observations of Io is rarely sufficient to resolve a ˜1 arc second Galilean satellite. However, Io is in phase locked orbit. Therefore, it is possible to longitudinally constrain the large scale distribution of spectrally active materials on Io's surface by ratioing spectra taken at different orbital longitudes. This technique constrains the hemispherical abundance of spectrally active absorbers by ratioing the spectra taken at different orbital longitudes to each other and comparing the relative strengths of the absorption features. However, it is difficult to constrain 30 degree longitude units by intercomparing direct full disk measurements. Furthermore, longitudinal compositional mapping by orbital phase variation techniques has ambiguities. These arise because the observer can never have absolute confidence that the spectral differences observed between full disk measurements at different phase angles represent the addition of a new absorber that was previously unobservable or the removal of an absorber that was previously observable as the object rotates.

In spite of these difficulties, observations with groundbased telescopes and from the International Ultraviolet Explorer (WE) spacecraft have shown that the two major components are asymmetrically distributed across Io's surface with the sulfur allotropes preponderant between longitudes 270 and 20 degrees and the SO_2 frost preponderant elsewhere (Nelson *et al.,* 1980, 1987 b).

Europa, like Ganymede and Callisto, is known from groundbased observations to have a surface predominately composed of water ice. All three icy Galilean satellites are absorbing at ultraviolet wavelengths and it is generally believed that one of the materials which darkens their surfaces is sulfur transported from the surface of Io by the Jovian magnetosphere. The spectra of Europa, Ganymede and Callisto are well characterized at the wavelengths utilized for these observations. In Europa's case, the sulfur ions are believed to impact the satellite's trailing side where they produce a spectral signature similar to SO_2 gas (Lane *etal.,* 1981). This may be true to a lesser extent on the other satellites. However, the low albedo of Ganymede and Callisto longward of 0.5 μm (where sulfur is very reflective) indicates that another darkening material in addition to sulfur must also be present. This species is currently unidentified (Nelson *et* al., 1987 b). For these occultation observations, any of the other Galilean satellites can serve as an appropriate comparison object because the spectral characteristics of all of them are weli known and the spectral contribution of the comparison object to the occultation lightcurve can be removed.

Previous attempts to use mutual occultations or eclipse reappearances of the Galilean satellites for the purpose of undertaking compositional mapping were constrained by two factors. The first was the large number of wavelength ranges that were monitored and the second was the lack of a stable high speed photometer to perform the observations. For example, Smith and Johnson (1979) attempted multi-spectral observations of the Galilean satellites at more than thirty wavelength intervals in the 0.32 μm- 1.1 μm range during eclipse reappearances of the satellites. They were able to infer the spectral differences of near-hemispherical sized areas on the satellites. The observations reported in this study measured the relative brightness change between only four wavelength regions of intermediate bandpass. These spectral regions were rapidly sampled at high signal to noise and this permitted many observations to be made during a typical eclipse of Io by another satellite. The suite of only four wavelengths that we employed was sufficient to constrain the distribution of the spectrally active surface components. By minimizing the number of wavelengths at which photometric data was taken we were able to achieve higher spatial resolution.

10's spectrum contains a strong absorption shortward of 0.33 μm which is seen in both the groundbased and the IUE data and a strong absorption shortward of 0.5 μm which is evident in the groundbased data. The absorption shortward of 0.33 μm is due to condensed SO_2 and the absorption shortward of 0.5 μm is due to sulfur Thus, bandpasses which sample Io's spectrum shortward of 0.33 μm, between '0.34-0.4 μm, between 0.42-0.48 μm, and longward of 0.56 μm define four spectral regions which determine the presence or absence of the two major species, sulfur and SO_2 frost (See Figure 2).

Photometric measurements at bandpasses which define the three shorter wavelength regions were ratioed to each other and to the photometric observations at 0.56 μm, where all the major chemical species which are believed to be present on Io's surface are extremely reflective. This technique of relative high speed photometry permits many precise measurements of the changes in the spectral ratios of the filter bandpasses to be made during the short time interval of the occultation.

The Observations

Twice in each Jupiter orbit about the sun the plane of the orbits of the satellites coincides with the plane of the ecliptic. In this circumstance, the satellites undergo mutual occultations from the perspective of an earth-based observer. During such an episode of mutual occultations, it is possible to monitor the electromagnetic radiation from one satellite as it passes in front of another. During the course of a particular occultation, the light from the occulted object is gradually obscured from an earth-based observer until the midpoint of the occultation. After this time, the radiation from the occulted object is gradually seen again.

Such occultations typically take ˜100 to ‘3000 seconds (depending on the geometry of a particular event) and this time is adequate for groundbased astronomical photometers to obtain the spatial resolution required to map the continental sized areas of a Galilean satellite.

Io’s spectral geometric albedo in the near uv-visual wavelength range is determined mainly by $S0_2$ frost, which causes a strong absorption shortward of 0.33 μm, and sulfur, which absorbs shortward of 0.75 μm. Assuming a simple two component model for the surface of Io which consists of sulfur and $S0_2$ frost, then the reflected radiation longward of 0.55 μm is due to the combined effect of sulfur and SO_2 frost, and the radiation reflected between 0.33 μm and 0.4 μm is due almost entirely to SO_2 frost only.

Multicolor high speed photometry at discrete wavelengths in the 0.32-0.56 μm range permits a relative comparison between spectral absorbers that are active in that spectral region. We identified four spectral regions of interest. Intermediate bandpass filters (fwhm ˜ 0.015 μm) centered at 0.56 μm, 0.4 μm, 0.345 μm, and 0.305 μm were sequentially placed in the lightpath of the photometer and these filters sampled the light at approximately 0.5 Hz frequency. Thus, depending on which filter was utilized, the light reflected from Io’s different compositional species could be isolated individually or in combination. As the eclipse progressed the color of the received light changed as different portions of Io’s surface were occulted. Of particular interest to this investigation was the change in the flux passed by the 0.305 μm filter compared to that passed by the 0.56 μm filter. These wavelengths represent the extremes in spectral contrast.

At wavelengths less that 0.32 μm, sulfur is more reflective than SO_2 and at wavelengths longer than 0.55 μm, SO_2 is more reflective than sulfur. Therefore, an SO_2 spot overlying an elemental sulfur background would appear to be bright against a dark background when viewed at 0.56 μm and the same spot would appear to be dark against a light background when observed at 0.33 μm. It is this contrast reversal that forms the basis of this compositional mapping technique.

Arlot (1988) identified 75 mutual occultation events in 1990-1991 in which Io was occulted by another Galilean satellite. The observations for this program had to be done when the sun is below the horizon and when the targets are at reasonable air mass. We identified those observations that occurred when the sun is below the horizon and the zenith distance is less than 70 degrees. We constrained the estimated magnitude drop to be at least O.O2 msg. There were 22 such events observable from McDonald Observatory that met these constraints. We attempted to observe all of these events. However frequent occurrences of cloudy weather only permitted us to observe 10 of them and only 2 of these were total eclipses. Five were of the polar regions only and the remaining three were at mid latitudes. The events that we observed and obtained data are summarized in Table 1.

Table 1

Date	Time	Duration (see)
01 Jan91	06h13m	2396
01 Jan91	]0h23m	1763
19 Jan91	05h28m	706
20Feb91	03h31m	465
27Feb91	05h41m	420
06Mar91	07h71m	374
13Mar91	10h01m	325
31 Mar91	03h32m	195
07Apr91	05h46m	142
09May91	03h59m	79

The McDonald Observatory P 45b, dual-beam, multichannel, high-speed photometer was used to rapidly sample all four band passes every 2.5 seconds during an occultation. The integration time for each channel was set independently to produce ‘ 1%

statistics for each data sample. A very blue sensitive photornultiplier, a RCA 8850 with negligible dark count at ambient temperatures was the detector in the first beam. A RCA 4516 was used in the secondary beam along with either a U or B filter to provide simultaneous light curve measurements of a nearby Galilean satellite. The light curve obtained in the second channel (usually that of Ganymede or Callisto) was used to monitor the atmospheric extinction during the occultation period. An entrance aperture of 5 arcsec was used to collect the light from Io and the occulting satellite. Although the seeing was usually much better, the 5 arcsec aperture was used to allow for any drift of the satellites during the occultation period. The background sky contamination from Jupiter was removed from each data sample by taking sky readings inside and outside Io's position on a radial line from Jupiter. An observing sequence usually consisted of integrations on the occultating satellite and Io when they were separated by >20 arcsec to remove the contribution of the occulting satellite.

The total area of Io occulted in this suite of occultations varied from ˉ590 to 100% depending on the event. Assuming that Eurpoa was the occulting object, this corresponds to a magnitude drop in the visual filter of 0.02 mag for a 5% occultation to 0.36 magnitudes for a 100% event. A typical occultation data set for a ˜800 second occultation consisted of ˜200 sets of four-filter data measurements each of which measured at the four wavelengths the drop in intensity going into occultation and the rise in intensity after mid occultation. Reduction of the data set consisted of:

1) Subtraction of scattered light from Jupiter that may enter the aperture (i.e. sky subtraction). Sky measurements were done before, during and after the occultation.

2) Subtraction of the reflected light contributed by the occulting satellite. The occulting object was observed before and after the occultation when it alone is in the field of view.

3) Selection of the necessary binning factor for each data set for co-adding data to assure good statistics.

4) Subtraction of the contribution to the signal from a typical measurement, n, from that of measurement n-l for the half of the observational set spanning the time from first contact to occultation midpoint. In addition, for the data from occultation midpoint to last contact, the signal from measurement n was subtracted from that of measurement n+1.

5) Establish the color ratio for each unit by ratioing the filter data to one another.

In order to simulate an occultation curve for comparison with the data we assumed that Io's entire surface was divided into 88 regions of approximately the same area. The number of regions assumed for this analysis was based on our best estimate of the spatial resolution that could be obtained using this technique. During a typical occultation the 44 regions which comprised the earth facing hemisphere were independently modeled assuming that the region had either the spectral properties of elemental sulfur or that it had the reflection properties of SO_2. The photometric properties of each region were approximated by a Minaert function.

The occultation geometry for a typical event (Jan 19, 1991) is shown in figure 3. Io is represented as a fixed object and Europa's position is shown relative to Io at 30 second intervals. Europa moved from left to right in the figure. If all parts of Io were uniformly bright the occultation profile through each filter would appear as shown in the computer simulation of Europa occulting a homogeneous Io the result of which appears as a solid line in figures 4 and 5. The observed data for the event are shown as points for the 0.305 μm (Fig 4) and 0,55 μm (Fig 5) filters respectively. The data from both filters are consistent with the hypothesis that Io's surface is photometrically inhomogeneous because different mineral species are asymmetrically distributed on Io's surface. This is evidenced by the displacement of the observed data from the simulation of a homogeneous Io.

The distribution of the sulfur and the SO_2 was varied on a trial and error basis in the model until the two events of 1 Jan 1991 could be simulated so as to produce a best fit between the two samples. These events were selected because they were total occultations. Then each successive nights data was added to the simulation assuming that ultimately all the data from all the nights had to be represented by one distribution of sulfur and SO_2. The product of this labor intensive process is shown is shown in figures 6 and 7. In both figures, the black region represents that part of Io which was never occulted during any of our successful set of observations. In Figure 6 the shaded gray area centered near longitude= 240 degrees and latitude=30 degrees N represents a region which is dark in the ultraviolet relative to its environs. This is consistent with the hypothesis that this region is comprised of $S0_2$ frost. Similarly, Figure 7 shows the same region is more reflective at 0.55 μm relative to its environs. This is the surface albedo distribution that Io would have when viewed through the 0.55 μm filter where the SO_2 is more reflective than the sulfur.

The occultation simulation for such a frost distribution on Io for the typical event of 19 Jan compared to the observation is shown in Figure 8 for the 0.305 μm filter. It is obvious that the distribution of SO_2 shown in Figure 6 simulates a much better fit to the observation than that expected from a homogeneous distribution of materials on Io's surface. Figure 9 shows the similar comparison between the simulation and the observation as expected for the 0.55 μm filter. The modeled data is the result of the distribution shown in figure 7. The distribution shown in figures 6 and 7 is the distribution of materials that simulated of the observations best.

Such a distribution of SO_2 frost, which is darker relative to its elemental sulfur environs at the wavelength of the 0.305 μm filter, would be brighter relative to its environs when viewed through the 0.55 μm filter. This is modeled as the lightest gray region in Figure 7 and the occultation simulation compared to the real data is shown in Figure 9.

Discussion

We have compared the region that we have identified as SO_2 frost with a Voyager clear filter composite image that is shown in Figure 10. The Voyager images are only able to identify the hypothesized SO_2 as being very reflective at all wavelengths available to the Voyager imaging system. No other compositional information can be inferred from the images. Although the resolution of our synthesized image is much coarser than the Voyager images our result provides strong, and conclusive evidence that the region is indeed SO_2 frost as distinguished from other white materials because our occultation observations can best be explained by a region of $S0_2$ frost located at 240,+30 which is very absorbing at 0.305 μm.

This result is consistent with the IUE result which fixed the SO_2 to this region of Io's surface and to longitudes of smaller size. Unfortunately, the geometry of the mutual occultation events was such that it was not possible to use this method to map Io's leading hemisphere.

The asymetric distribution of materials on Io's surface has several possible explanations. McEwen and Soderblom (1983) suggested that Io has two types of volcanic plumes. They attributed the first type to SO_2 geysers as suggested by Kieffer (1982). They suggest that this type of eruption predominates the plumes found on Io's leading hemisphere and includes all of Io's trailing hemisphere and covers the trailing hemisphere to longitudes of near 240 degrees as suggested in the IUE data. The other type of volcano has sulfur as its primary ejected material The ejects from the sulfur volcanos covers 10's surface between longitudes 250 degrees to 360 degrees.

Sack *et al.* (1993) have noted that Io's leading to trailing hemisphere spectral ratio can be simulated by irradiating a mixture of vapor deposited SO_2 ice and an $SO_2/H_2S/H_2O$ ice mixture. They suggest that the Jovian magnetospheric particles sweeping past Io might create a similar irradiation environment on the materials comprising Io's trailing hemisphere. Thus, particle bombardment might explain Io's irregular spectral distribution.

We suggest that the results of this investigation imply that SO_2 covers a sufficient portion of Io's trailing hemisphere in a manner that is inconsistent with spectral alterations due to magnetospheric particle irradiation. While spectral changes due to particle bombardment may be happening on Io, it is possible to explain the spectral changes seen during a series of occultations by an inhomogeneous distribution of expected surface materials. Radiation induced color changes in Io's surface materials cannot be ruled out, they merely are not required to explain the observed albedo distribution.

Acknowledgements

We thank Jay Lieske for providing accurate ephemerides for this observational set. We thank Ed Duchover for assisting with the astronomical observations and Martin Villareal for his support of the data transfer operations from McDonald Observatory to JPL. The support of the entire McDonald Observatory staff is deeply appreciated. We acknowledge the generosity of Glen Orten for sharing lending his computer to us for processing our data. We thank Al McEwen for providing us with a digital image of Io. This work represents one phase of research performed at the Jet Propulsion Laboratory under contract with NASA.

References

Arlot, J. E. (1988). The localization of the volcanic hot spots of Io by the occultation method in 1901. *Astron. and Astrophys., suppl. series, 76, 495-499.*

Fanale, F.P. et al (1979). Significance of absorption features in Io's reflection spectrum. *Nature,* 280, 760-763.

Goguen, J. D., W. M. Sinton, D. L. Matson, R. R. Howell, H. M. Dyck, T. V. Johnson, G. J. Veeder, A. L. Lane, R. M. Nelson, R. A. McLaren, (1988). Io hot spots: Infrared photometry of satellite occultations. *Icarus, 76, 465-484.*

Hapke, B.W., (1971). In PHYSICAL STUDIES OF THE MINOR PLANETS, NASA SP-267, 67-77.

Hapke, B. W. (1981). Bidirectional reflectance spectroscopy 1. Theory. *J. Geophys. Res.,* 86, 3039-3054.

Hapke, B. W. (1984). Bidirectional reflectance spectroscopy 3. Correction for macroscopic roughness. Icarus, *59,* 41-59.

Hapke, B. W. (1989). Coherent backscatter: An explanation for the unusual properties of outer solar system planetary bodies. *Bull. Am. Astron.* Sot., 21, 984.

Kieffer, S. W. (1982). Dynamics and thermodynamics of volcanic eruptions: Implications for the plumes of Io. In *The Satellites of Jupiter,* D. Morrisson cd., University of Arizona Press, Tucson, pp. 647-773.

Lane, A. L., R. M. Nelson and D. L. Matson (1981). Evidence for sulphur implanta-ion in Europa's uv absorption band. *Nature, 292, 38-39.*

Lillie, C. F. , C. W. Herd, K. Pang, D. L. Coffeen, J. E. Hansen (1977). The Voyager Mission Photopolarimeter Experiment. Space *Sci. Rev.,* 21, 159-181.

Matson, D. L., F. P. Fanale, T. V. Johnson, 1974. Sodium D-line emission for Io: Sputtering and resonant scattering hypothesis, Astrophys. J. Let., 192, L43-L46.

Meyer, B., M. Gouterman. D. Jensen, T. V. Oomen, 1972. The spectrum of sulfur and its allotropes. In Advances in Chemistry Series #l IO. Sulfur Research Trends, American Chemical Society, Washington,

McEwen, A. S. and L. A. Soderblom (1983). Two classes of volcanic plumes on Io. *Icarus, 55*, 191-217.

Nelson, R. M. and B. W. Hapke (1978). Spectral reflectivities of the Galilean satellites and Titan, 0.32-0.86 micrometers. *Icarus,* 36, 304-309.

Nelson, R. M., A. L. Lane, D. L. Matson, F. P. Fanale, D. B. Nash, T. V. Johnson (1980). Io: Longitudinal distributional of sulfur dioxide frost. Science, 210, 784-786.

Nelson, R. M., A. L. Lane, D. L. Matson, G. J. Veeder, B. J. Buratti, E. F. Tedesco (1987). Spectral Geometric albedos of the Galilean satellites from 0.24 to 0.34 micrometers: Observations with the International Ultraviolet Explorer. *Icarus,* 72, 358-380.

Nelson, R. M. and A. L. Lane, (1987). 'Planetary Satellites' Chapter 4 of the volume Exploring the Universe with the IUE Satellite, D. Reidel, Dordrecht, Y. Kondo ed.

Nelson, R. M. , W. D. Smythe, B. W. Hapke, A. J. Cohen (1990). On the effect of X rays on the color of elemental sulfur: Implications for Jupiter's satellite Io. *Icarus,* 85, 326-334.

Smith, D. W. and P. E. Johnson. (1979). Eclipse spectrophotometry of the Galilean satellites. *Icarus, 39, 251-256.*

Smythe, W. D., R. M. Nelson, D. B. Nash, (1979). Spectral evidence for $S0_2$ frost or adsorbate on Io. *Nature,* 280, 766.

Wamsteker, W., R. L. Kroes, and J. A. Fountain (1974). On the surface composition of Io. *Icarus,* 10, 1-7.

Figure Captions

Fig la. Spectral geometric albedo of Io from 0.26 to 0.34 μm from observations with the International Ultraviolet Explorer Spacecraft (after Nelson and Lane, 1987). Fig **1,b.** Spectral geometric albedo of Io from 0.33 to 0.6 μm from observations with groundbased telescopes (after Nelson and Hapke, 1978). The shaded area in the figures is the wavelength range of the four filters used for this study.

Fig. 2 Spectral reflectance measured in the laboratory of two hypothesized surface components of Io (after Nelson *et* al., 1990). The broken line is the reflectance of SO_2 frost (after Nash *et* al., *1980). The* solid line is the spectral reflectance of a mixture of elemental sulfur allotropes (Nelson *et* al., 1990) plus a small amount of unknown dark material of low albedo. The shaded area shows the wavelength range of the filters selected or this study.

Fig 3. Occultation geometry of typical event where Europa passes in front of Io obscuring progressively larger regions of Io's surface and then exposing them again. The geometry is for the event of 19 Jan 1992.

Fig. 4. The line is the simulation of the occultation profile assuming that Io had a homogeneous surface. The points are the data as seen through the 0.31 μm filter.

Fig. 5. Same as figure 4 except for the 0.55 μm filter.

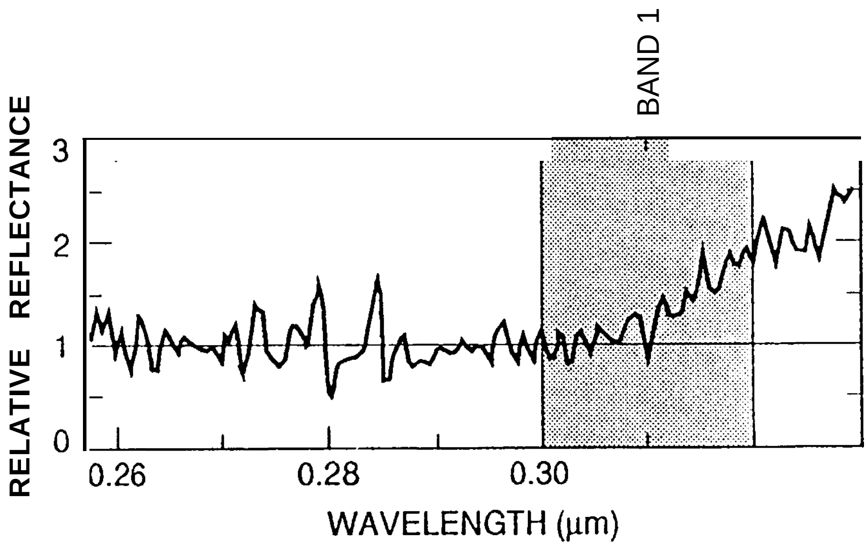
Fig. 6. Hypothesized distribution of SO_2 frost on Io in order to provide the best occultation fit in the 0.305μm filter data. The simulation in this case is shown in figure 8.

Fig 7. Same as figure 6 except for the 0.55 μm filter.

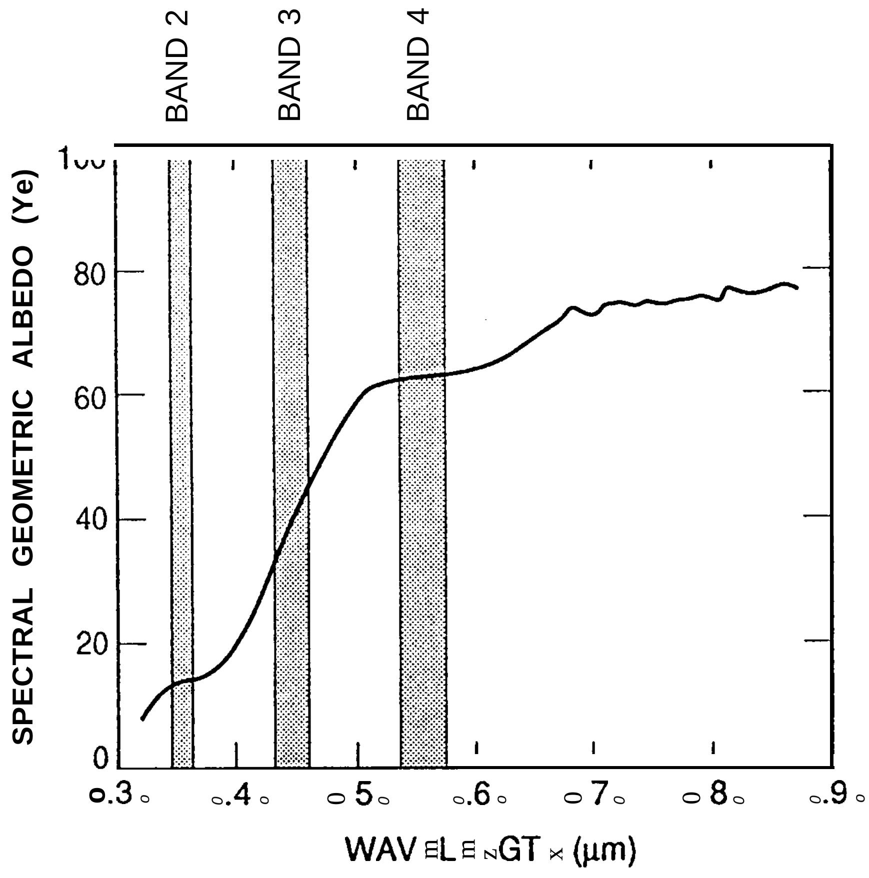
Fig. 8. Occultation profile expected from the 0.305μm filter assuming the SO_2 frost were distributed as in figure 6.

Fig 9. Same as figure 8 except for the 0.55 μm filter.

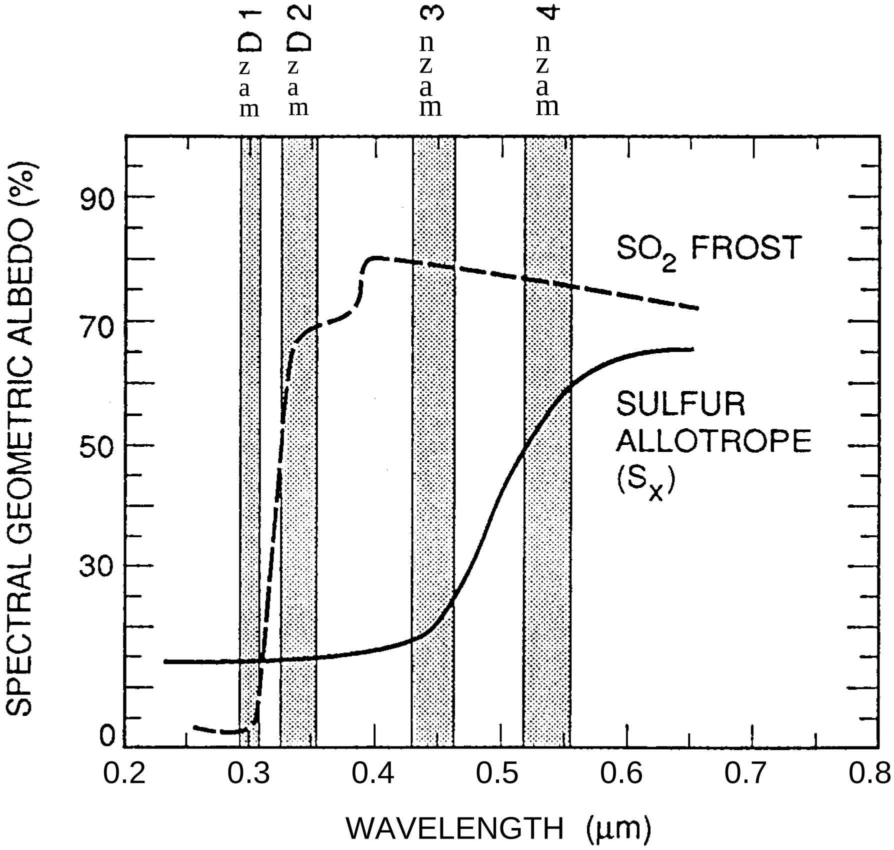
Fig 10. Voyager clear filter mage of 10. T ıe white region is the area where this study identifies SO_2 frost.

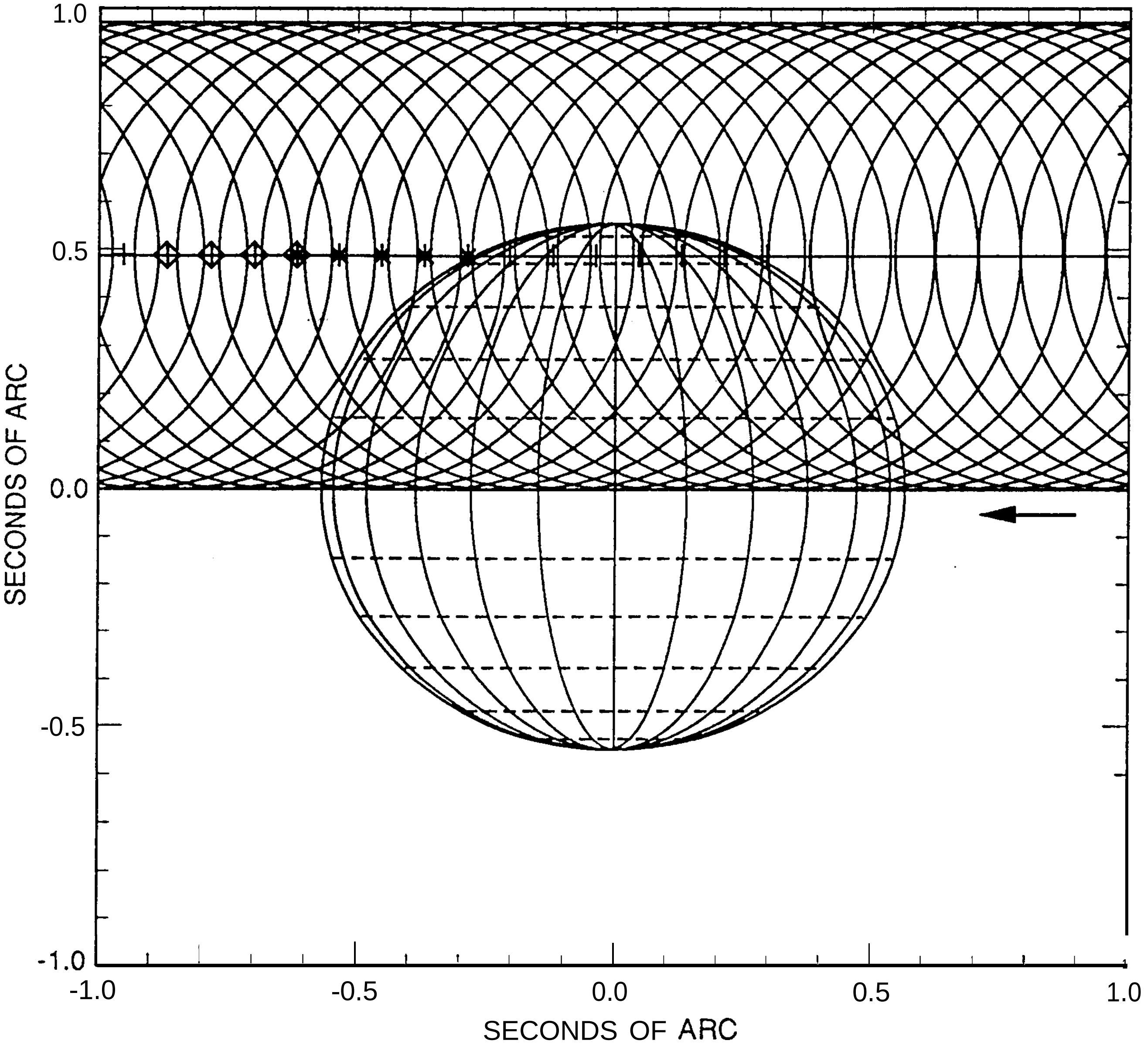


IUE

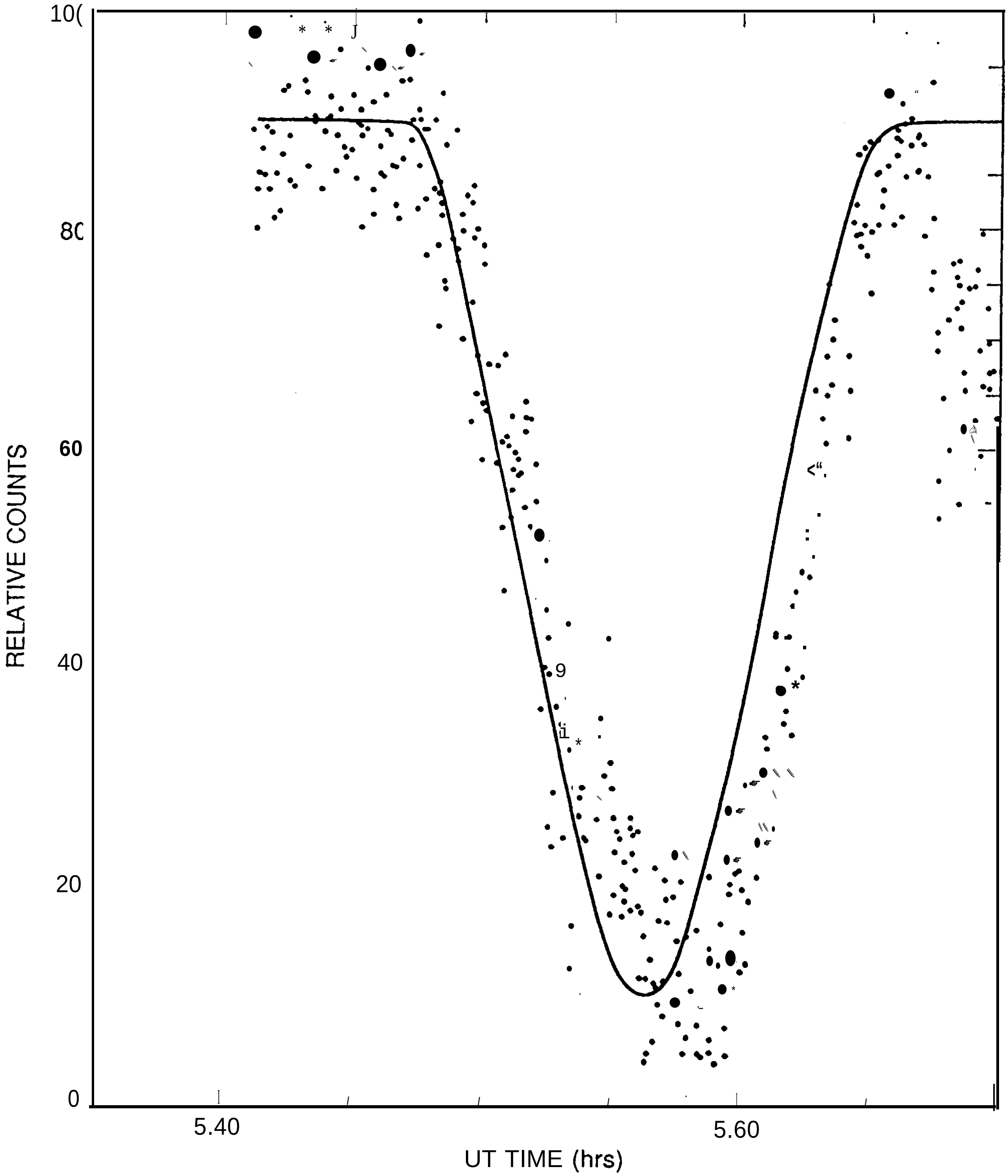


GROUND BASED

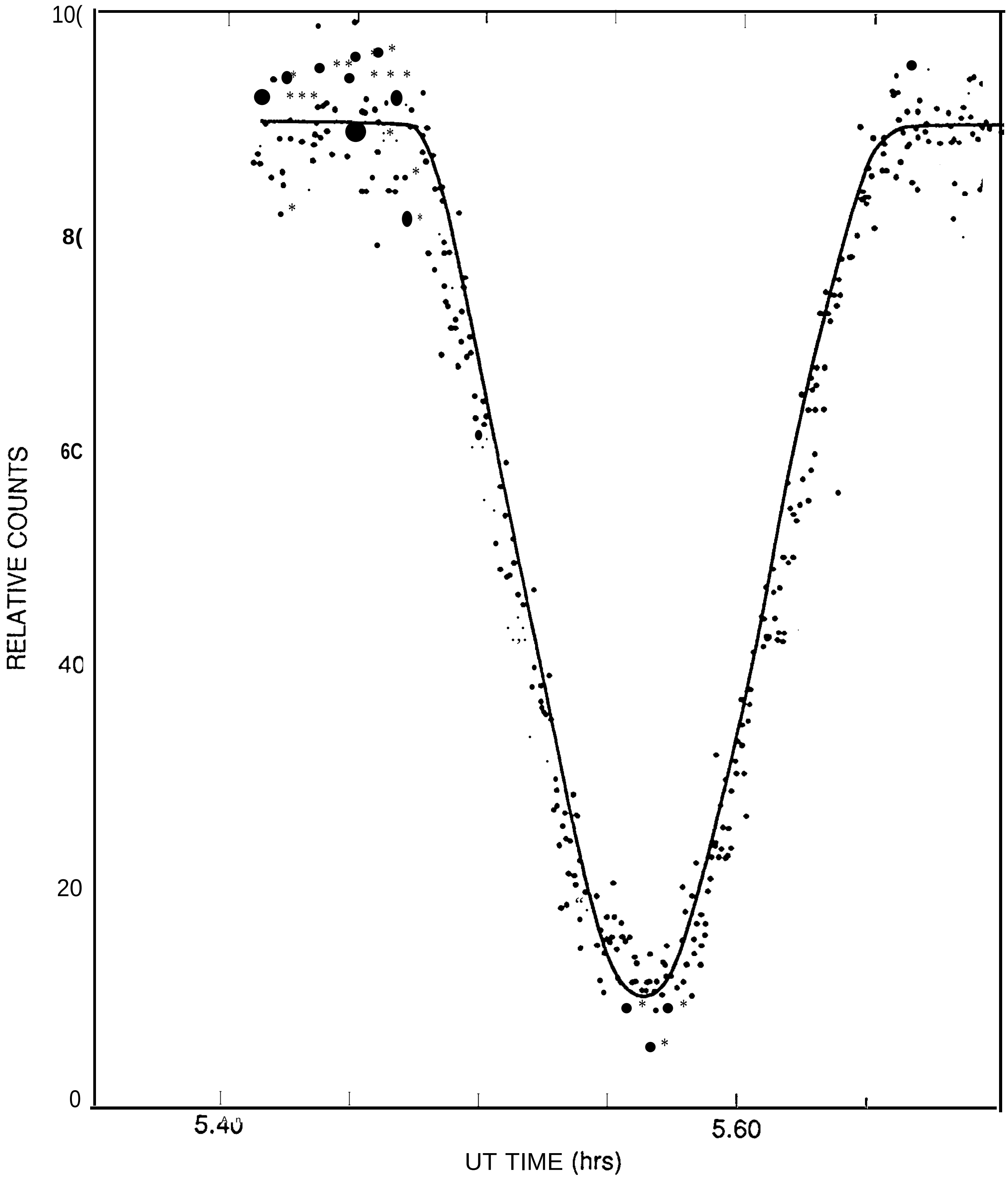

SPECTRAL GEOMETRIC ALBEDO (%)
90
70
50
30
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
WAVELENGTH (μm)
SO2 FROST
SULFUR
ALLOTROPE
(SX)



1.0
0.5
0.0
-0.5
-1.0
SECONDS OF ARC
-1.0
-0.5
0.0
0.5
1.0
SECONDS OF ARC

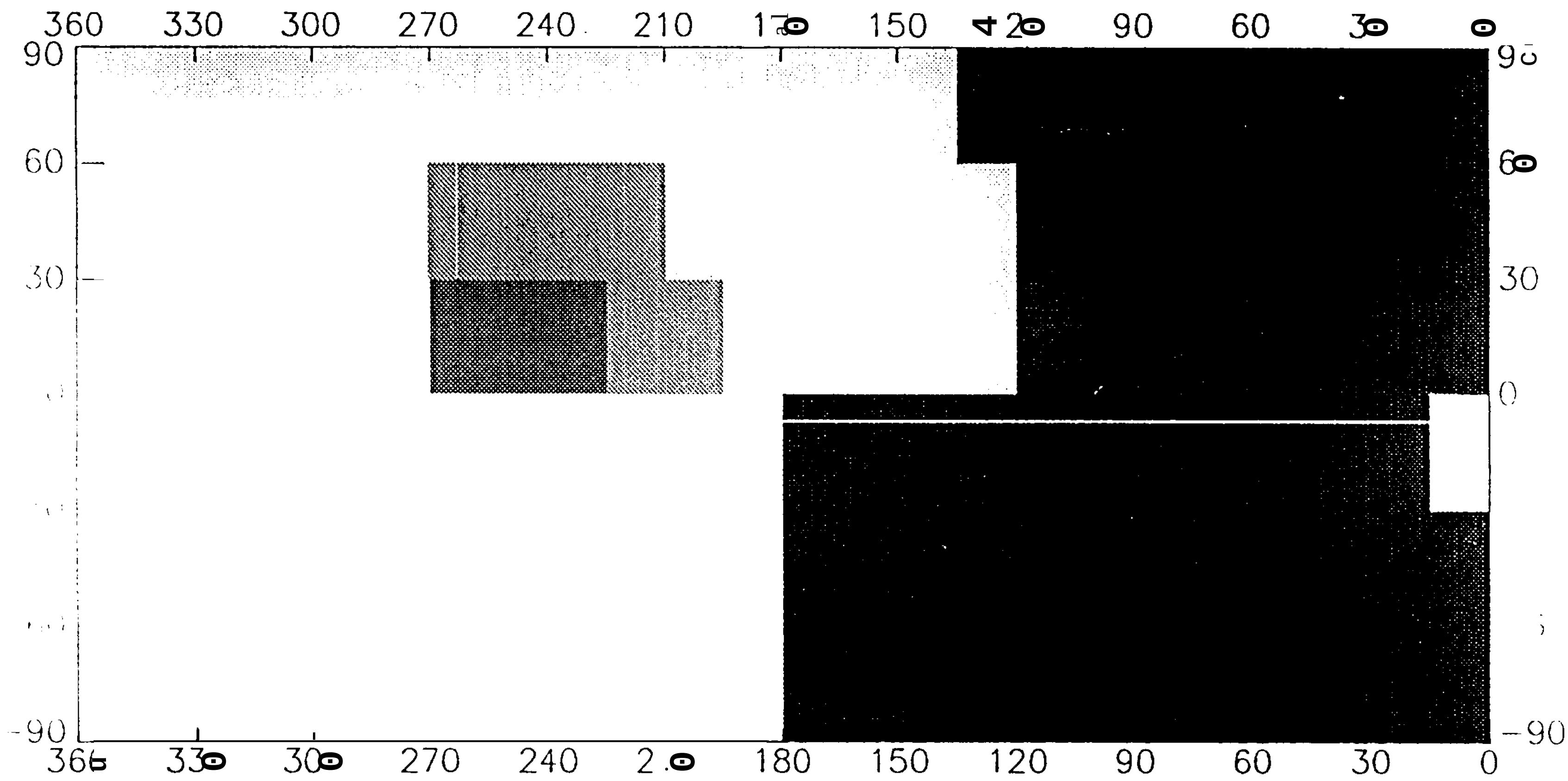


10(
80
60
40
20
0
RELATIVE COUNTS
5.40
5.60
UT TIME (hrs)

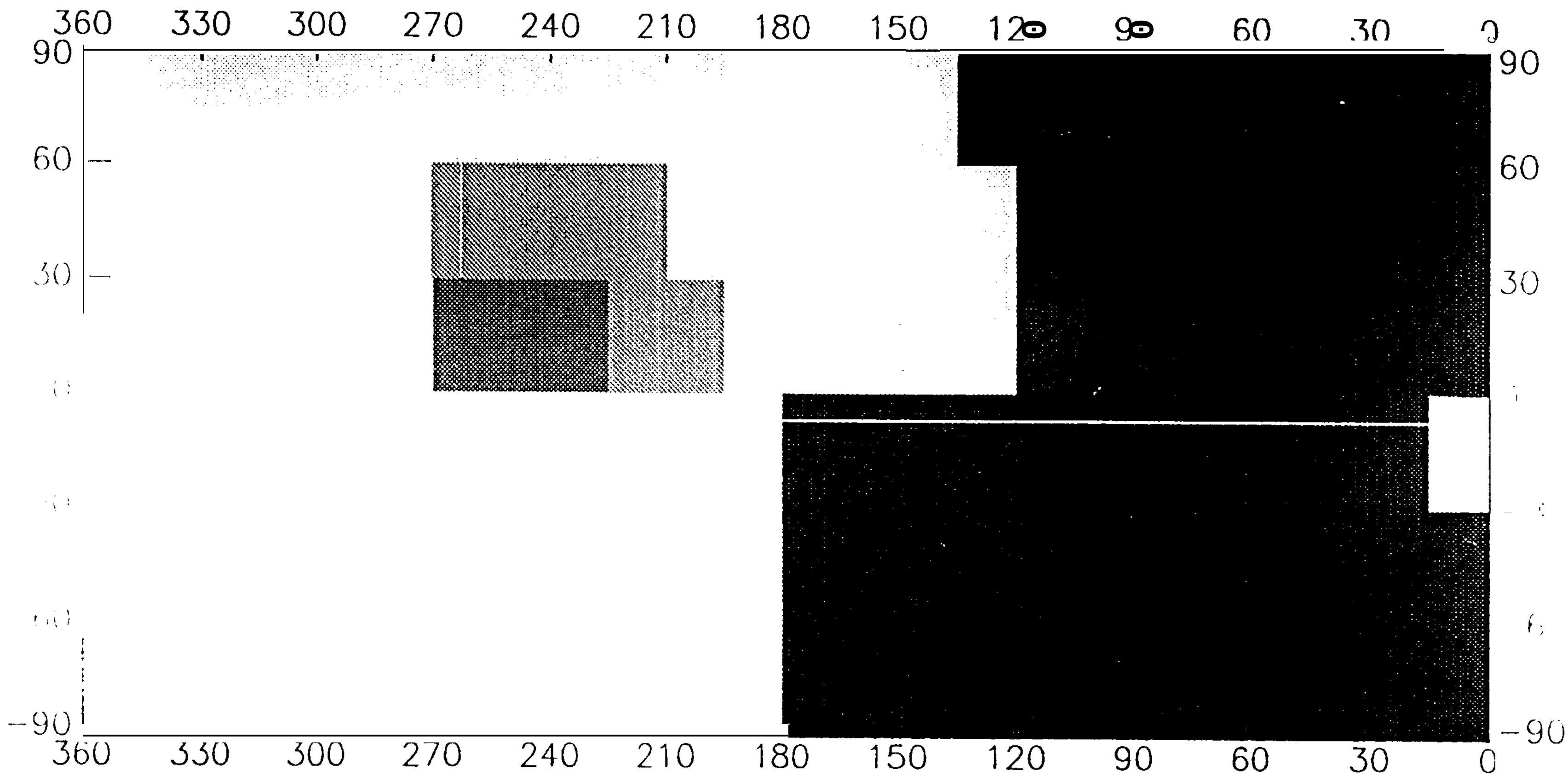


10(
8(
6C
40
20
0
RELATIVE COUNTS
5.40
5.60
UT TIME (hrs)

0.305

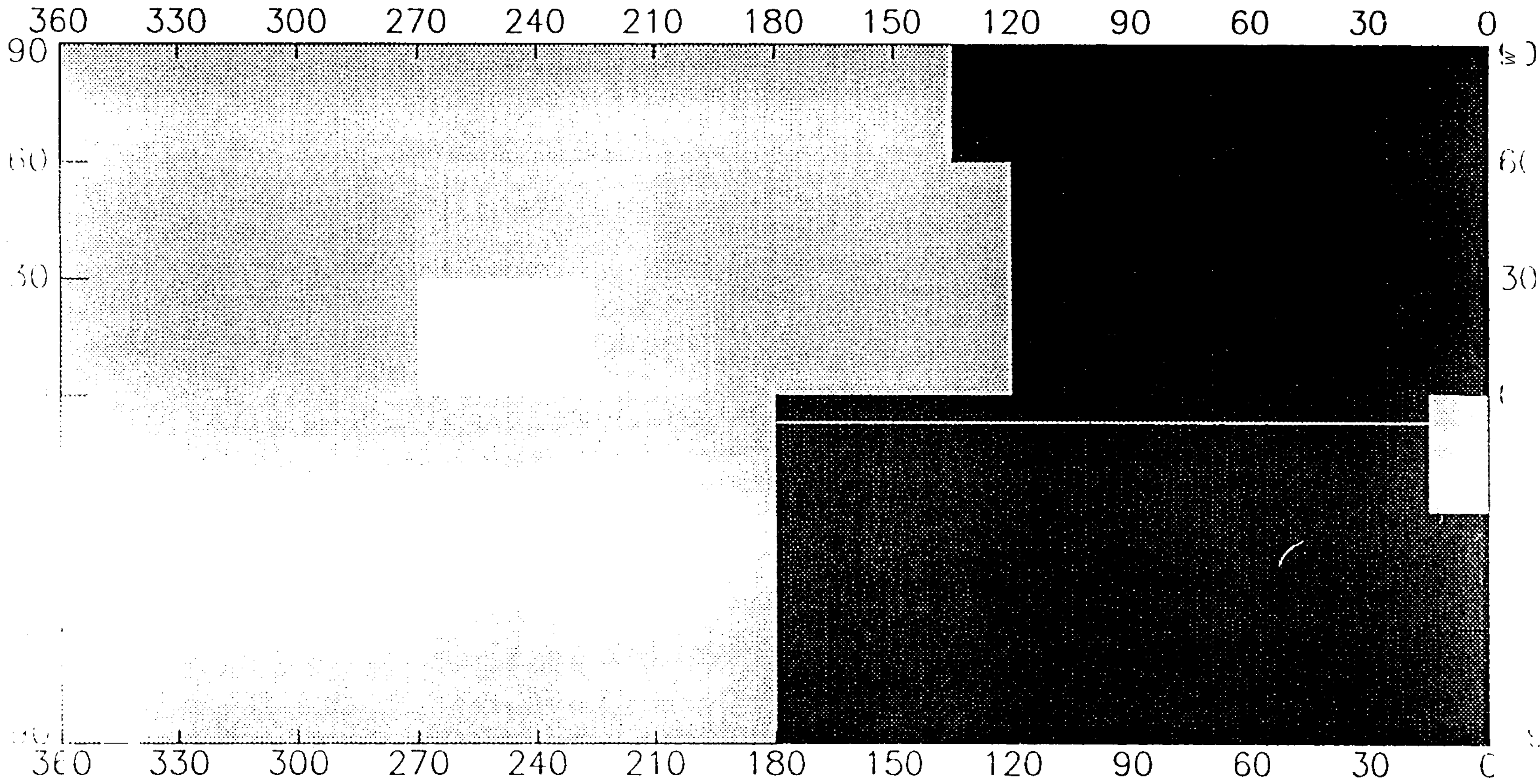


0.305

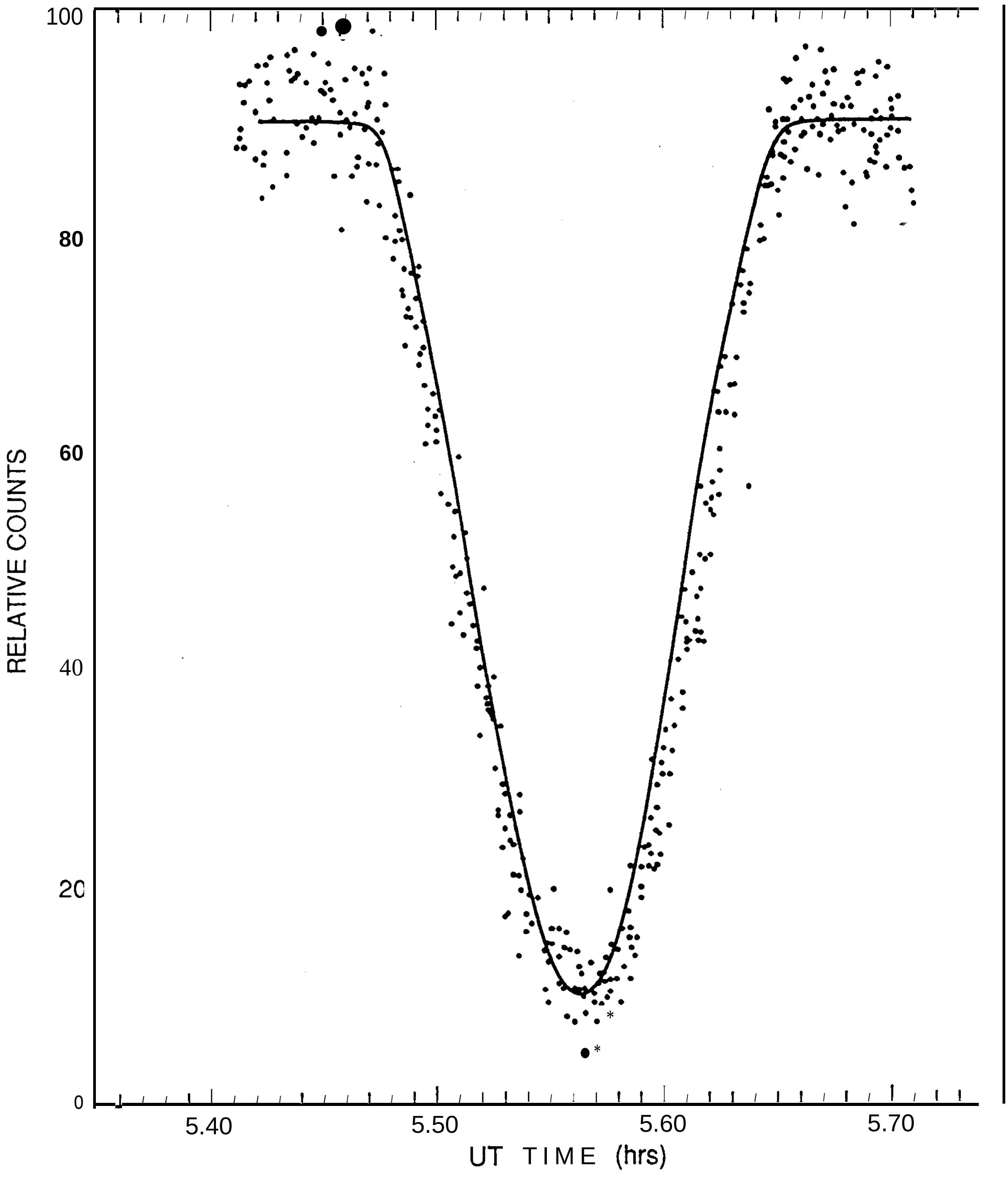


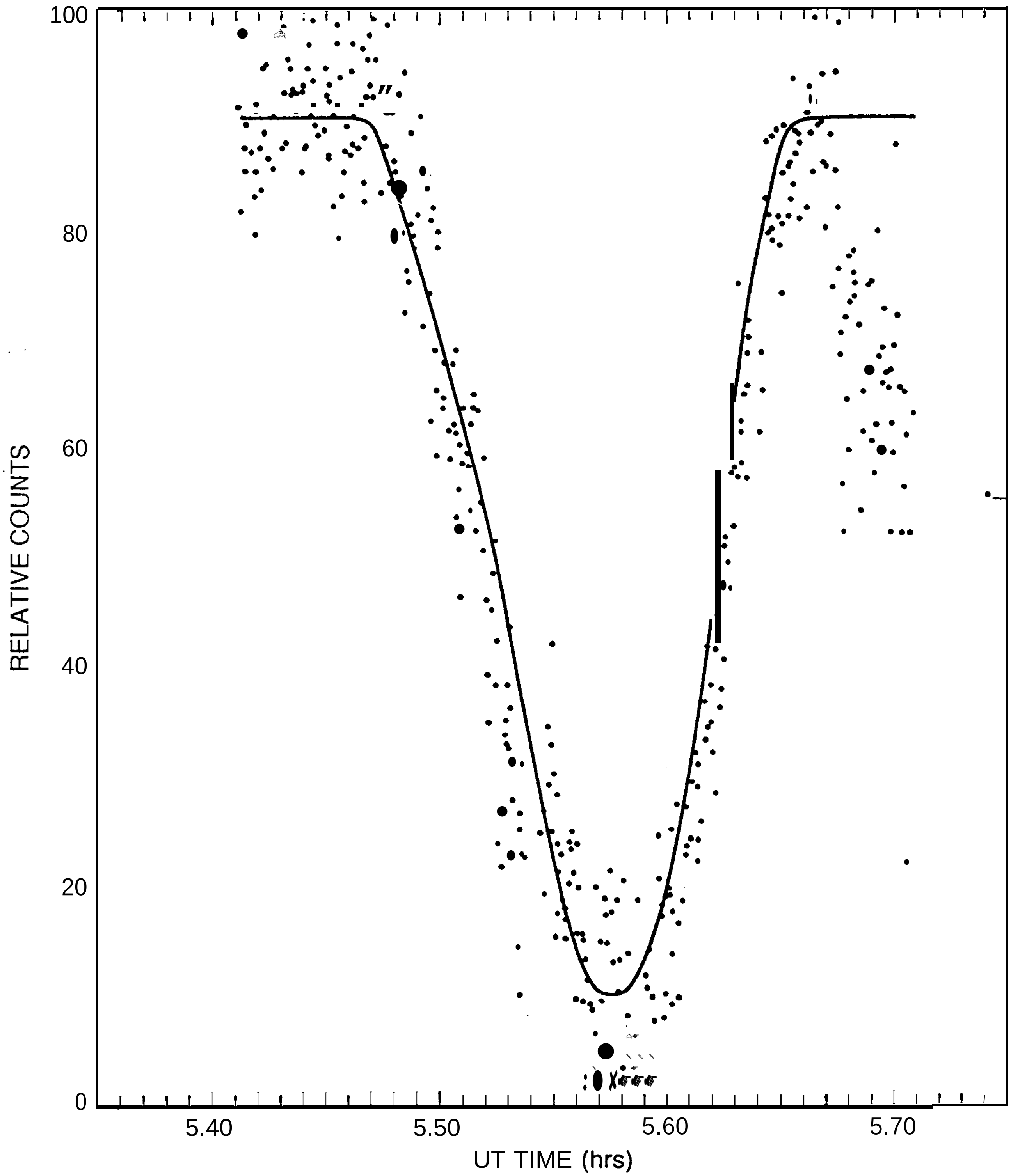
lb

0.55



(7)


100
80
60
40
20
0
RELATIVE COUNTS
5.40
5.50
5.60
5.70
UT TIME (hrs)



RELATIVE COUNTS
100
80
60
40
20
0
5.40
5.50
5.60
5.70
UT TIME (hrs)

k